

AFFDL-TM-73-40-FXG

AIR FORCE FLIGHT DYNAMICS LABORATORY
DIRECTOR OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT PATTERSON AIR FORCE BASE OHIO



CALIBRATION OF THE PEBBLE BED
HEATED FACILITY

Richard R. Smith
James A. Funderburg

High Speed Aero Performance Branch
Flight Mechanics Division
Air Force Flight Dynamics Laboratory

April 1973

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Project No. 1366
Task No. 136601

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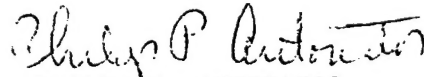
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Air Force Flight Dynamics Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by Richard R. Smith and James A. Funderburg of the High Speed Aero Performance Branch, Flight Mechanics Division, Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, Ohio. The work was accomplished in-house under Project 1366, "Aeroperformance and Aeroheating Technology" Task Nr. 136601, "Aerodynamic Analysis and Evaluation Techniques". This report describes the Mach 10 calibration tests completed in the High Temperature Pebble Bed Heated Facility (HTF).

This technical memorandum has been reviewed and is approved.



PHILIP P. ANTONATOS
Chief, Flight Mechanics Division
Air Force Flight Dynamics Laboratory

ABSTRACT

The Air Force Flight Dynamics Laboratory High Temperature Pebble Bed Heated Facility test section was re-calibrated using the 150 inch long Mach 10 contoured nozzle. Measurements made with the 8-tube impact pressure rake indicate the nozzle is producing satisfactory flow for continued aerodynamic testing.

Selected results of the calibration runs are presented in this report to show the test section Mach number distribution variation with stagnation pressure and axial station.

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SECTION I

INTRODUCTION

The AFFDL Temperature Pebble Bed Heated Facility (HTF) is a blow-down wind tunnel which provides a Mach 10 moderate Reynolds number simulation.

First operational in 1969, the capability of this facility has included testing with Mach 9, 10, 11 and 12 nozzles. The Mach 10 contoured nozzle was found to provide the best test flow and is the Mach number most frequently required for test programs. This nozzle was made using a design originally developed for one of the Naval Ordnance Laboratory's wind tunnels.

This report presents selected results of one periodic calibration study to verify usefulness of the test section flow.

SECTION II

APPARATUS

HIGH TEMPERATURE FACILITY (HTF)

The AFFDL High Temperature Facility (HTF) is a blowdown wind tunnel which uses a refractory pebble-bed heater as its heat source. Figure 1 shows a schematic of the general arrangement of the tunnel circuit and associated systems.

The pebble-bed heater is a combustion fired storage heater using refractory oxide pebbles as the storage medium. The heater is regenerated between test runs with an air-oxygen-propane burner which outputs 1.5×10^5 BTU/hr at idle conditions and 1.5×10^6 BTU/hr at maximum heating rates. The current heater configuration consists of 3/8 inch diameter alumina pebbles with the pebble core being 28 inches in diameter and 15 feet in depth.

The axisymmetric nozzle currently used in the tunnel is 150 inches in length and has a 24 inch exit diameter. The nozzle is a contoured and water cooled nozzle. The throat section is designed to be interchangeable with throats for other Mach numbers. The Mach 10 throat is the only one currently available. Figure 2 shows the nozzle details. Three nozzle exit orifices, each 120° apart, are manifolded together for nozzle exit static pressure measurement.

The test section is the free-jet type and is surrounded by a sealed plenum chamber to provide the necessary boundary conditions for parallel shock-free flow in the test section.

The model injection system consists of two model mounting struts placed 90 degrees apart on a carriage-mounted pivot. Both struts are out of the airstream when the tunnel flow is started. When flow is established, either strut can be rotated into the airstream and locked into position within approximately .75 seconds. Pitch of the model is accomplished by motion of the model strut along a pitch sector, giving an angle of attack range of ± 30 degrees. The model injection system and pitch mechanism are mounted on a carriage which can be moved axially a distance of 11 inches. Figure 3 shows the model support system.

CALIBRATION EQUIPMENT

The calibration equipment consists of an 8-tube water cooled impact pressure rake fabricated from beryllium copper, Figure 4. The 8 tubes are spaced over a span distance of 10 inches with tubes 1 and 2 located 1/2 inch on either side of the tunnel centerline when the rake is in the injected position. Spacing of the remainder of the tubes is 1 1/2 inches. Each tube is water-cooled and is 0.375 inch OD, 0.0625 ID, and spherically blunted.

INSTRUMENTATION

Tunnel stagnation pressure is measured in the pebble-bed heater with a 1000 psia transducer. The rake impact pressures are measured with consolidated control corporation "Ultradyn" pressure transducers as are nozzle static and test cabin pressure. Transducer ranges and reference pressures used for the rake, nozzle static and test cabin pressure measurements are presented in Table 1.

The signals from the transducers are amplified by Natel Engineering Co. 3KHZ carrier amplifiers. These analog voltages are then digitized using a Control Data Corp. 8032C Analog/Digital converter and stored on magnetic tape. Final reduction of data is then done using a Control Data Corp. 160-A computer.

A Chromel-Alumel thermocouple located in the low velocity region upstream of the nozzle throat is used to measure the test stagnation temperature.

TABLE I
Instrumentation

| Transducer Use | Transducer Size (PSID) | Full-Scale Calibration | Reference Press (PSIA) |
|-------------------|---------------------------|---------------------------|---------------------------|
| Nozzle Static | 0-to-.1 | 0.1 | 0 |
| Rake Impact | 0-to-2.0 | 2.0 | 0 |
| Diffuser Static | 0-to-.1 | 0.1 | 0 |

SECTION III

TEST DESCRIPTION

TEST PROCEDURE

With the test cabin evacuated to 0.02 psia, the pebble-bed heater is pressurized. At approximately 100 psia heater pressure, a rubber plug in the nozzle throat is blown out whereupon hypersonic flow is established in the test section. The heater stagnation pressure is then raised to that desired for the test run. At this time, the impact pressure rake is rotated into the airstream and data is recorded. The rake is moved axially from 1.0 inch from the nozzle exit to 9 inches downstream with data recorded at each station.

A summary of tunnel conditions and impact pressures for each tube during the calibration runs is presented in Table II.

DATA REDUCTION PROCEDURES

Pressures were calculated using average readings for all scans of a single burst of data. A Mach number was calculated at each rake tap location from the measured rake pressure and the measured tunnel stagnation pressure. The relation for a perfect gas is presented in Reference 1 as

$$\left[\frac{P_r}{P_o} \right]_{\text{perf}} = \left\{ \frac{(\gamma+1) M^2}{(\gamma-1) M^2 + 2} \right\}^{\frac{\gamma}{\gamma-1}} \left\{ \frac{\gamma+1}{2\gamma M^2 - (\gamma-1)} \right\}^{\frac{1}{\gamma-1}} \quad (1)$$

Since the measured pressures from the tunnel are assumed thermally perfect but calorically imperfect because of the sufficiently high temperatures, a correction factor, $K_3 = f(M, T_o)$ was applied to Equation 1 and $\gamma = 1.40$ was incorporated. The correction factor incorporated in the present data reduction program was empirically found to be a fourth order curve fit of stagnation temperature. The resulting equation used in the Mach number calculation then is

$$\frac{P_r}{P_o} = K_3 \left\{ \frac{6M^2}{M^2 + 5} \right\}^{\frac{7}{2}} \left\{ \frac{6}{7M^2 - 1} \right\}^{\frac{5}{2}} \quad (2)$$

The calculation of Mach number using Equation 2 was an iterative process whereby a nominal value of M was inserted for the first

calculation of P_r/P_o , M was then adjusted during succeeding calculations until the calculated value of P_r/P_o equaled the ratio measured in the wind tunnel.

The details of the data reduction program are contained in Reference 2.

SECTION IV

DISCUSSION OF RESULTS

Figures 5 through 11 present selected results of the calibration runs using the 8-tube impact pressure rake. Table II is a summary of the data collected for the runs shown in these figures. The isometric view represent the calculated test section Mach number distribution as derived from the impact pressure rake as a function of both axial and radial distance.

Water does form in the heater during periods of heat regeneration since it is a product of the combustion of propane. To minimize the effect of water vapor in the test medium the heater is evacuated prior to runs. The results of this procedure are presented in Figures 5 through 9. As can be seen the results are close to the nominal Mach 10.0 design of the nozzle. As a point of comparison Figures 10 and 11 present Mach number distributions for 300 and 600 PSIA stagnation pressures where evacuation was not carried out prior to running. The deviation from the distributions in the earlier figures is as much as 0.2 in Mach number near the centerline. This is explained by the different impact pressure that is measured when water vapor in the air-stream condenses in the nozzle throat area. Thus during routine model testing, a single tube impact pressure measurement is made in close proximity to the model. This allows a Mach number calibration each time model pressure, force or heat transfer measurements are made.

The radial distribution of Mach number in Figures 5 through 9 is

TABLE 11

WTF CALIBRATION DATA

| RUN | PA PSIA | TO DEG R | PT2(MM HG) N077LF EXIT | TURE 1 (-0.5) | TURE 2 (.5) | TURE 3 (2.0) | TURE 4 (3.5) | TURE 5 (5.0) | TURE 6 (6.5) | TURE 7 (8.0) | TURE 8 (9.5) |
|--------|------------|-------------|---------------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 71-198 | 100.1 | 2113.3 | 1.0 PT2(MM HG) WACH | 16.562 9.66 | 16.362 9.68 | 15.926 9.74 | 15.418 9.81 | 15.016 9.87 | 14.046 10.02 | 10.701 10.69 | 6.117 12.09 |
| 71-198 | 106.5 | 2117.9 | 3.0 PT2(MM HG) WACH | 17.581 9.66 | 17.349 9.69 | 16.952 9.74 | 16.385 9.81 | 15.936 9.87 | 15.001 10.01 | 11.471 10.67 | 6.578 12.06 |
| 71-198 | 109.2 | 2147.5 | 5.0 PT2(MM HG) WACH | 18.141 9.64 | 17.875 9.67 | 17.570 9.71 | 17.115 9.76 | 16.584 9.83 | 15.584 9.98 | 11.901 10.63 | 6.721 12.06 |
| 71-198 | 104.2 | 2131.7 | 7.0 PT2(MM HG) WACH | 17.162 9.66 | 16.828 9.70 | 16.565 9.74 | 16.214 9.78 | 15.796 9.84 | 14.980 9.96 | 11.636 10.57 | 6.387 12.08 |
| 71-100 | 97.1 | 2152.2 | 9.0 PT2(MM HG) WACH | 16.188 9.63 | 15.992 9.66 | 15.827 9.68 | 15.618 9.71 | 15.154 9.77 | 14.238 9.91 | 10.877 10.56 | 5.815 12.13 |
| 71-200 | 200.7 | 2104.1 | 1.0 PT2(MM HG) WACH | 29.217 9.94 | 29.037 9.96 | 28.893 9.97 | 28.497 10.00 | 28.664 9.99 | 29.838 9.84 | 25.027 10.31 | 14.866 11.63 |
| 71-200 | 200.6 | 2156.4 | 3.0 PT2(MM HG) WACH | 28.788 9.96 | 28.703 9.97 | 28.932 9.95 | 29.073 9.94 | 29.448 9.91 | 30.002 9.87 | 25.757 10.22 | 15.478 11.52 |
| 71-200 | 200.8 | 2149.9 | 5.0 PT2(MM HG) WACH | 28.612 9.98 | 28.331 10.00 | 28.304 10.01 | 28.209 10.01 | 28.370 10.00 | 29.196 9.92 | 24.566 10.35 | 14.455 11.69 |
| 71-200 | 201.6 | 2136.0 | 7.0 PT2(MM HG) WACH | 28.456 10.01 | 28.145 10.03 | 28.196 10.03 | 28.228 10.02 | 28.468 10.00 | 29.338 9.94 | 24.336 10.38 | 13.719 11.83 |
| 71-200 | 202.5 | 2176.0 | 9.0 PT2(MM HG) WACH | 28.526 10.00 | 28.315 10.02 | 28.399 10.01 | 28.817 9.98 | 29.301 9.94 | 29.758 9.90 | 25.299 10.29 | 13.643 11.85 |
| 71-41 | 303.1 | 2236.6 | 1.0 PT2(MM HG) WACH | 42.744 9.99 | 42.047 9.97 | 43.676 9.94 | 43.598 9.94 | 43.292 9.96 | 44.750 9.88 | 36.925 10.34 | 21.037 11.76 |
| 71-41 | 303.1 | 2261.1 | 3.0 PT2(MM HG) WACH | 42.402 10.00 | 42.363 10.00 | 42.927 9.97 | 42.725 9.98 | 42.895 9.97 | 44.610 9.89 | 37.594 10.29 | 21.522 11.70 |
| 71-41 | 303.3 | 2272.9 | 5.0 PT2(MM HG) WACH | 42.402 10.00 | 42.112 10.02 | 42.668 9.98 | 42.697 9.98 | 42.987 9.97 | 44.192 9.90 | 37.594 10.29 | 22.202 11.62 |
| 71-41 | 303.7 | 2273.4 | 7.0 PT2(MM HG) WACH | 42.240 10.01 | 41.813 10.03 | 42.497 10.00 | 42.619 9.99 | 42.697 9.99 | 44.326 9.90 | 37.271 10.31 | 22.123 11.63 |
| 71-41 | 304.0 | 2270.5 | 9.0 PT2(MM HG) WACH | 42.193 10.02 | 41.776 10.04 | 42.395 10.01 | 42.683 9.99 | 42.895 9.98 | 44.080 9.92 | 36.130 10.39 | 22.853 11.56 |

TABLE 11 - CONTINUED

WTF CALIBRATION DATA

| RUN | P0 PSIA | T0 DEG R | DISTANCE FROM NOZZLE EXIT | TUBE 1 P-0.5) | TUBE 2 (.5) | TUBE 3 (2.0) | TUBE 4 (3.5) | TUBE 5 (5.0) | TUBE 6 (6.5) | TUBE 7 (8.0) | TUBE 8 (9.5) |
|--------|------------|-------------|------------------------------|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 72-424 | 300.8 | 2398.7 | 1.0 | PT2(MM H ₂ O) WACH | 42.085 9.97 | 42.536 9.94 | 41.976 9.97 | 41.411 10.00 | 40.268 10.07 | 41.241 10.01 | 35.195 10.39 |
| 72-424 | 208.1 | 2470.9 | 3.0 | PT2(MM H ₂ O) WACH | 41.785 9.95 | 42.361 9.92 | 42.180 9.93 | 42.119 9.93 | 40.893 10.00 | 41.727 9.96 | 35.544 10.34 |
| 72-424 | 209.5 | 2470.3 | 5.0 | PT2(MM H ₂ O) WACH | 42.472 9.92 | 42.038 9.89 | 42.726 9.90 | 42.420 9.92 | 41.346 9.98 | 41.728 9.96 | 34.728 10.38 |
| 72-424 | 300.4 | 2471.9 | 7.0 | PT2(MM H ₂ O) WACH | 42.887 9.90 | 43.139 9.89 | 42.996 9.89 | 42.904 9.90 | 41.795 9.96 | 42.249 9.93 | 35.296 10.36 |
| 72-424 | 299.4 | 2452.9 | 9.0 | PT2(MM H ₂ O) WACH | 42.851 9.90 | 42.788 9.90 | 42.523 9.92 | 42.436 9.92 | 41.271 9.99 | 41.942 9.95 | 34.908 10.39 |
| 71-42 | 508.9 | 2297.0 | 1.0 | PT2(MM H ₂ O) WACH | 70.299 10.02 | 70.443 10.03 | 71.042 10.01 | 69.674 10.05 | 69.302 10.06 | 71.290 10.00 | 62.268 10.32 |
| 71-42 | 510.4 | 2287.2 | 3.0 | PT2(MM H ₂ O) WACH | 69.680 10.06 | 70.522 10.03 | 71.021 10.02 | 69.681 10.06 | 69.248 10.08 | 71.218 10.01 | 62.787 10.31 |
| 71-42 | 509.5 | 2284.4 | 5.0 | PT2(MM H ₂ O) WACH | 69.468 10.07 | 70.851 10.02 | 71.248 10.01 | 69.959 10.05 | 69.157 10.08 | 71.030 10.01 | 63.845 10.27 |
| 71-42 | 507.7 | 2294.7 | 7.0 | PT2(MM H ₂ O) WACH | 69.255 10.06 | 70.450 10.02 | 71.175 10.00 | 70.531 10.02 | 69.356 10.06 | 70.841 10.01 | 62.274 10.32 |
| 71-42 | 506.4 | 2290.7 | 9.0 | PT2(MM H ₂ O) WACH | 69.554 10.05 | 70.009 10.03 | 70.527 10.01 | 69.982 10.03 | 68.484 10.08 | 70.026 10.03 | 63.147 10.28 |
| 71-195 | 602.2 | 2510.4 | 1.0 | PT2(MM H ₂ O) WACH | 90.043 9.80 | 90.116 9.80 | 87.364 9.87 | 85.900 9.91 | 85.637 9.91 | 76.579 10.17 | 47.237 11.40 |
| 71-195 | 602.5 | 2500.3 | 3.0 | PT2(MM H ₂ O) WACH | 89.248 9.82 | 89.618 9.81 | 86.837 9.88 | 84.737 9.94 | 84.677 9.94 | 84.357 9.95 | 76.517 10.18 |
| 71-195 | 604.1 | 2495.1 | 5.0 | PT2(MM H ₂ O) WACH | 87.210 9.88 | 87.846 9.87 | 85.696 9.92 | 83.488 9.98 | 83.203 9.98 | 83.203 9.99 | 75.893 10.21 |
| 71-195 | 606.3 | 2504.7 | 7.0 | PT2(MM H ₂ O) WACH | 87.828 9.87 | 88.412 9.86 | 86.454 9.91 | 83.868 9.98 | 83.484 9.99 | 83.209 10.00 | 76.043 10.21 |
| 71-195 | 605.5 | 2511.9 | 9.0 | PT2(MM H ₂ O) WACH | 88.704 9.85 | 89.251 9.83 | 87.805 9.87 | 85.063 9.94 | 84.353 9.96 | 84.203 9.96 | 77.516 10.16 |

seen to be less than 0.1 in Mach number over a 5-inch distance from the tunnel centerline. This gives a 10-inch diameter flow core which is sufficient for testing and is consistent with tunnel blockage limitations.

The axial distribution of Mach number in Figures 5 through 9 is also seen to be less than 0.1 Mach over the 8 inches that measurements were made. Although most models tested range from 12 to 15 inches in length, there is no indication in the figures that flow discontinuities might exist further downstream from the 9-inch station and the flow is considered satisfactory.

Reference 3 shows some of the results from water vapor effects. Care must be taken in facility operation to assure that correct data is being generated. As a result of the water vapor investigation operational procedures have been established which appear to give creditable results.

SECTION V

CONCLUSIONS

The results of the calibration of the HTF test section flow indicate

- a. There has been no erosion of the throat.
- b. The test core is approximately 10 inches at 100 psia and 14 inches at 600 psia.
- c. Mach number gradients are small in both the radial and axial direction about 1%.
- d. Proper operating procedures must be used to minimize water vapor effects.

REFERENCES

1. AMES Research Staff, Equations, Tables, and Charts for Compressible Flow, NACA Report 1135, 1953
2. Hillsamer, Max E., Calibration of the AFFDL High Temperature Gasdynamic Facility with the 80-Inch Long Nozzle System Installed, FDM TM 67-5, Oct 1967.
3. Smith, R.R., "Results of Water Vapor Condensation in the Nozzle of a High Mach Number Wind Tunnel," To be Published.

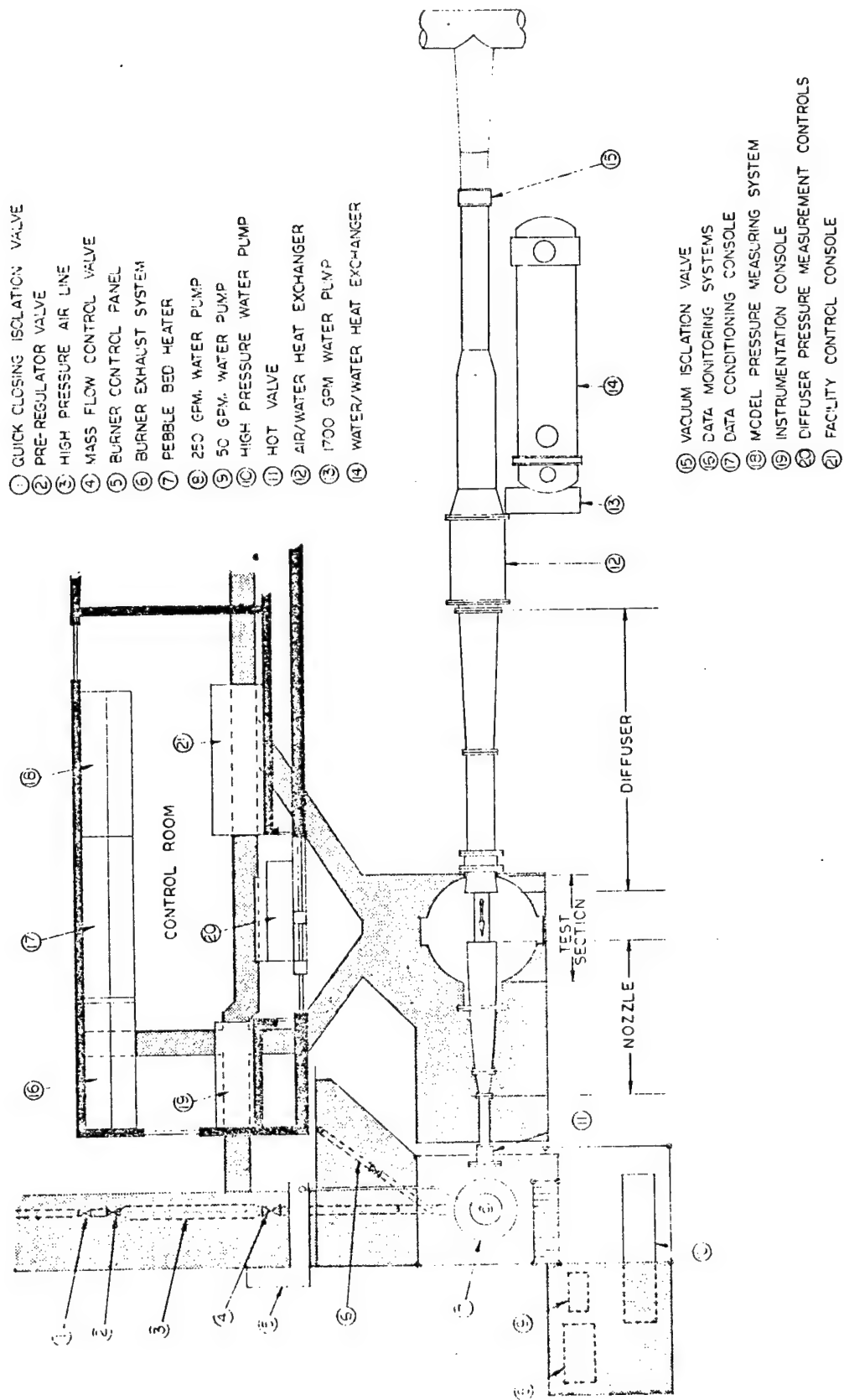


FIGURE 1. GENERAL ARRANGEMENT OF HIGH TEMPERATURE FACILITY

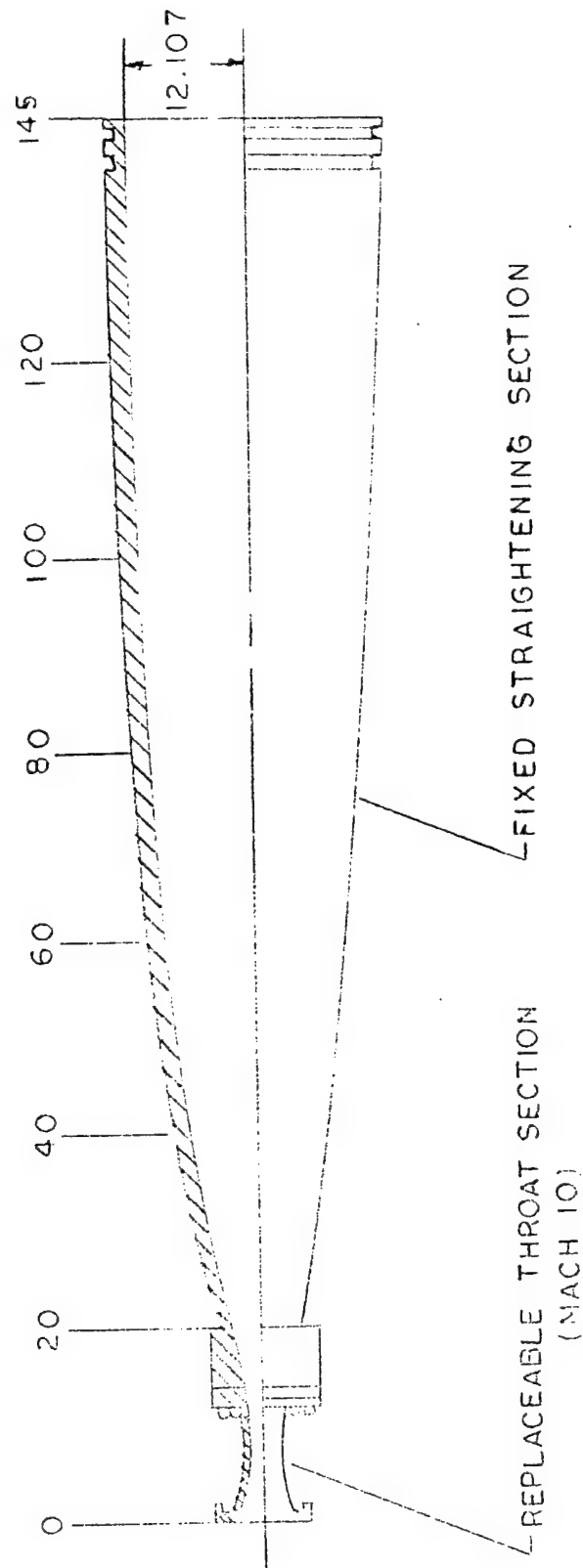


Figure 2 Mach 10 Nozzle

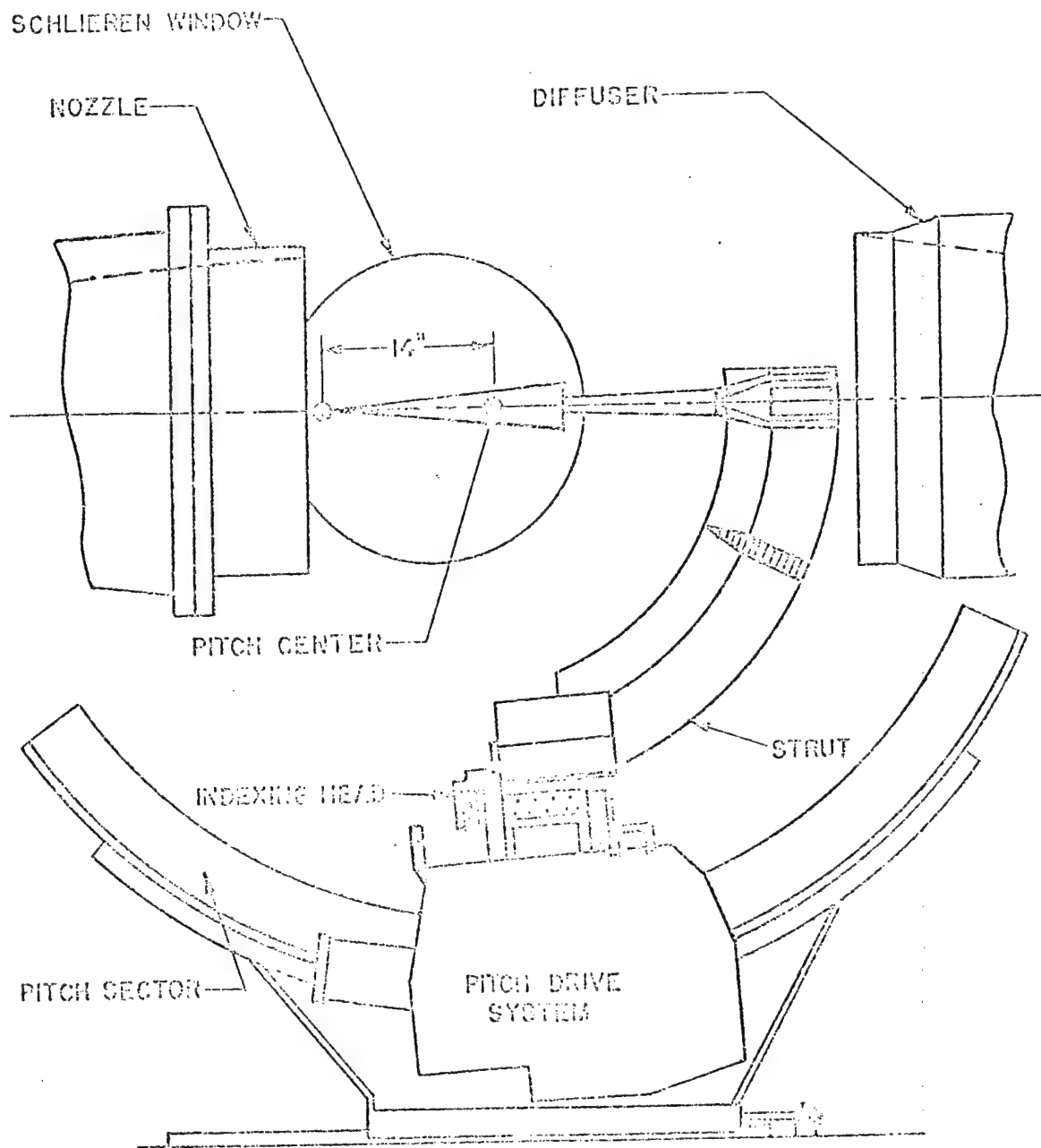


FIGURE 3 - Model Support Carriage

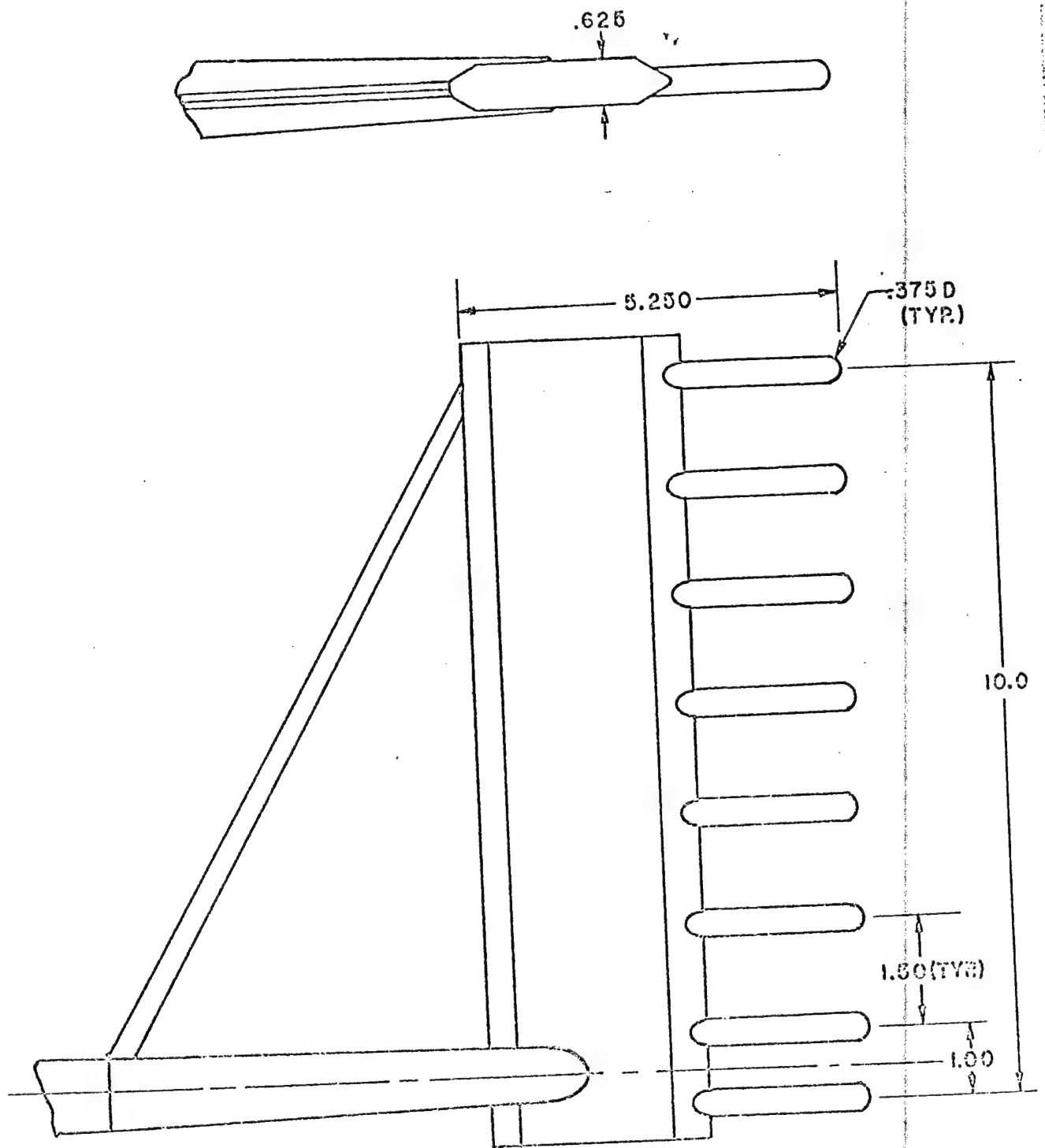


Figure 4 Total Pressure Rake

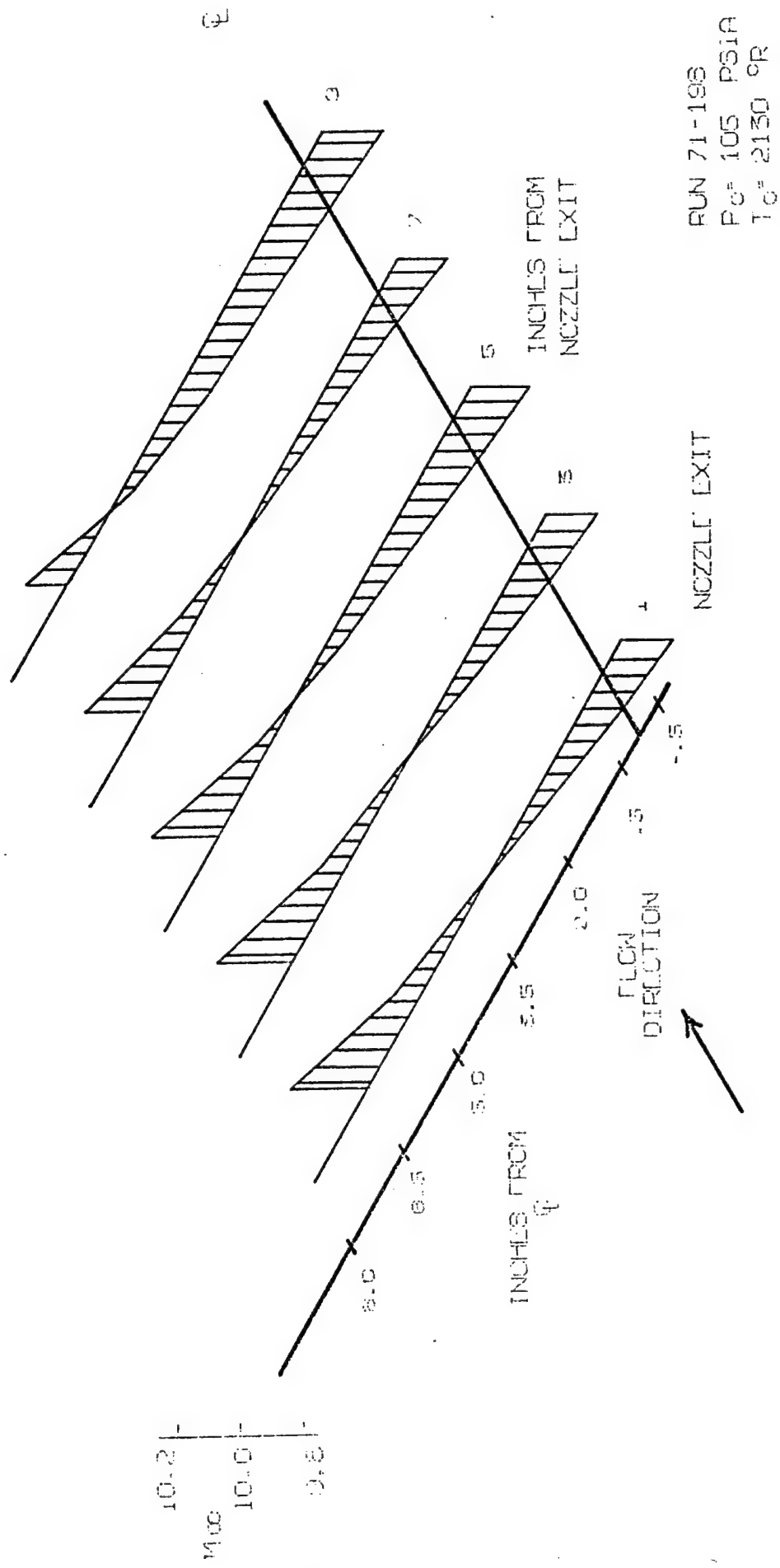


Figure 5 Mach Number Distribution $P_0 = 100 \text{ PSIA}$

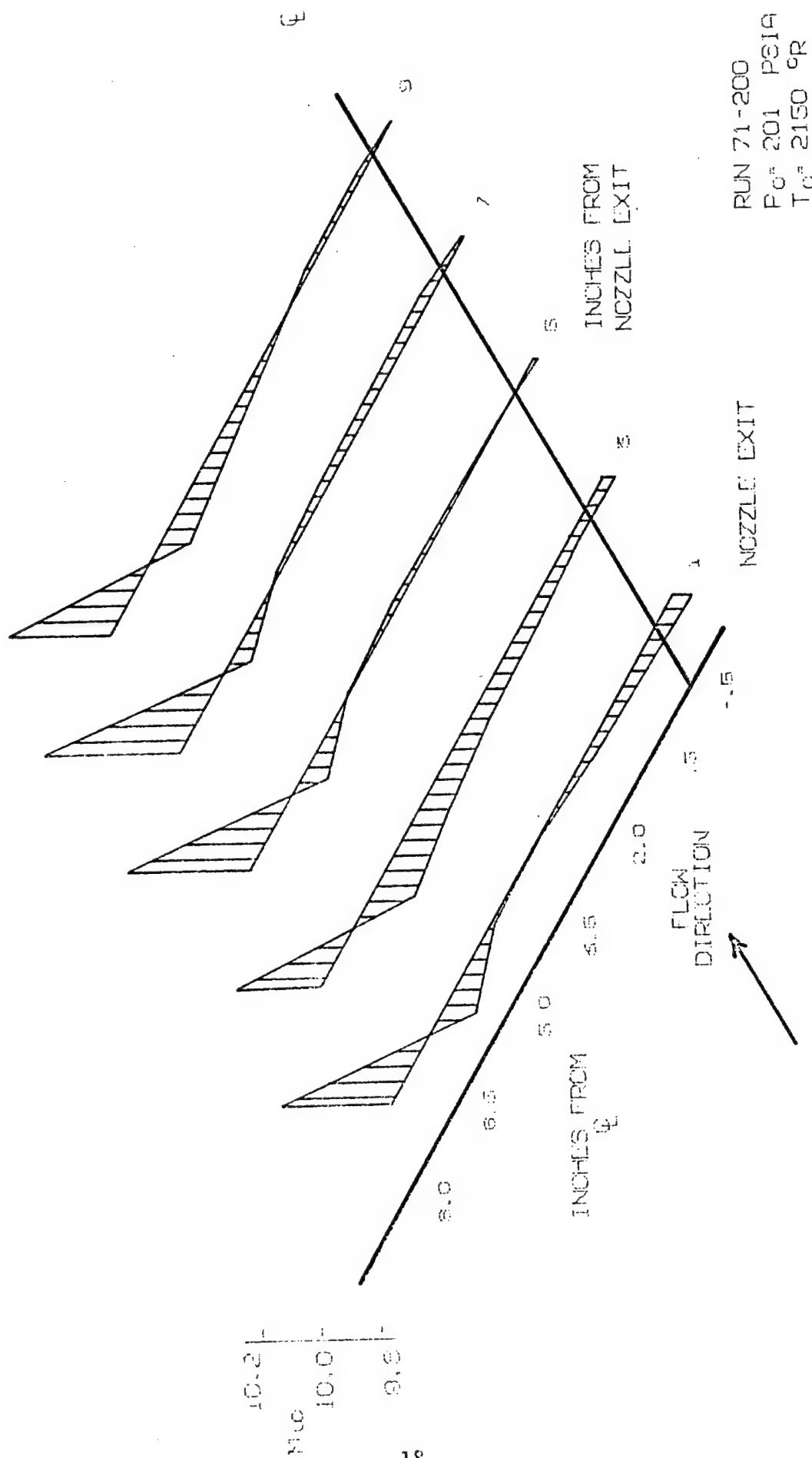


Figure 6 Mach Number Distribution $P_0 = 200$ PSIA

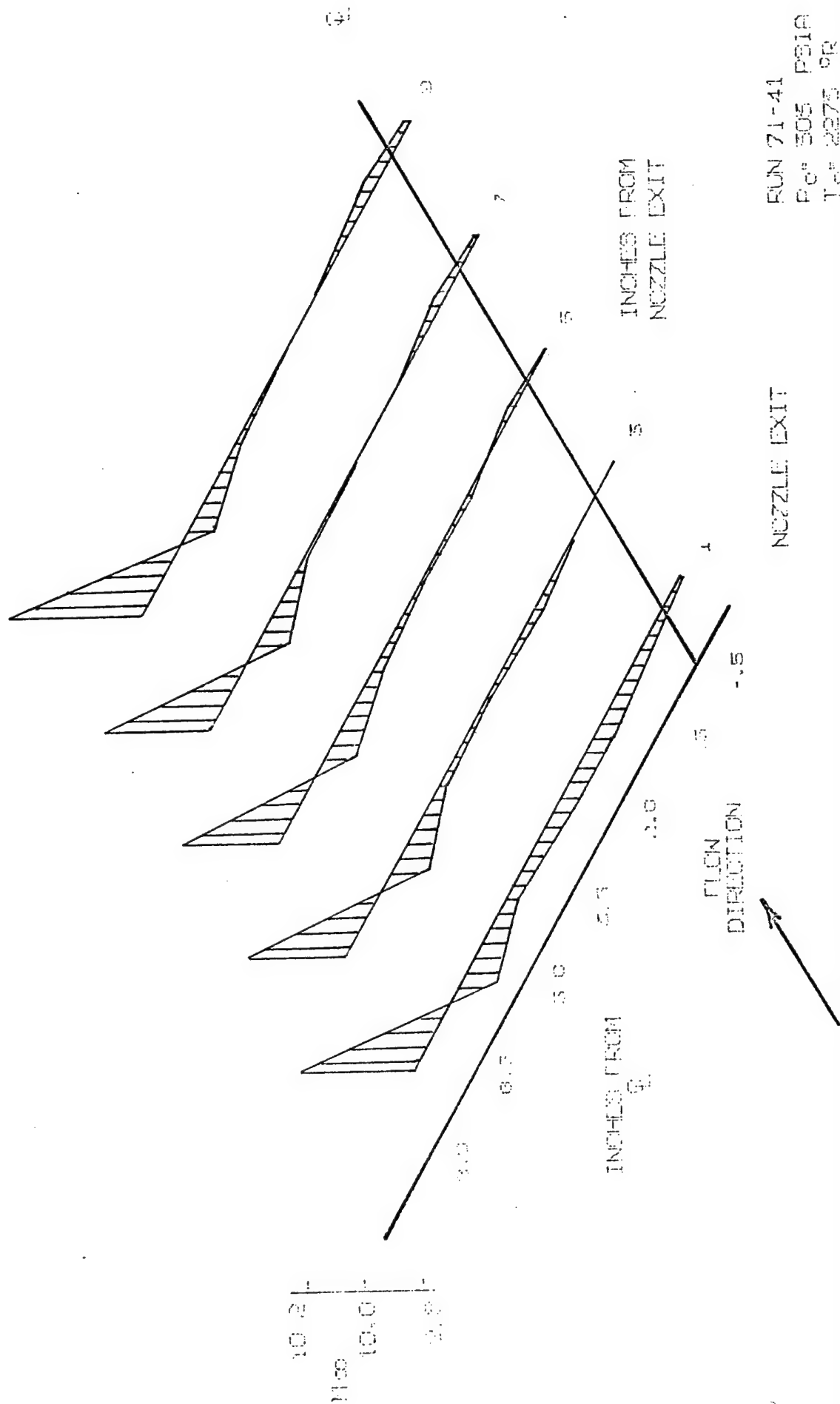


Figure 7 Mach Number Distribution $P_0 = 300$ PSIA

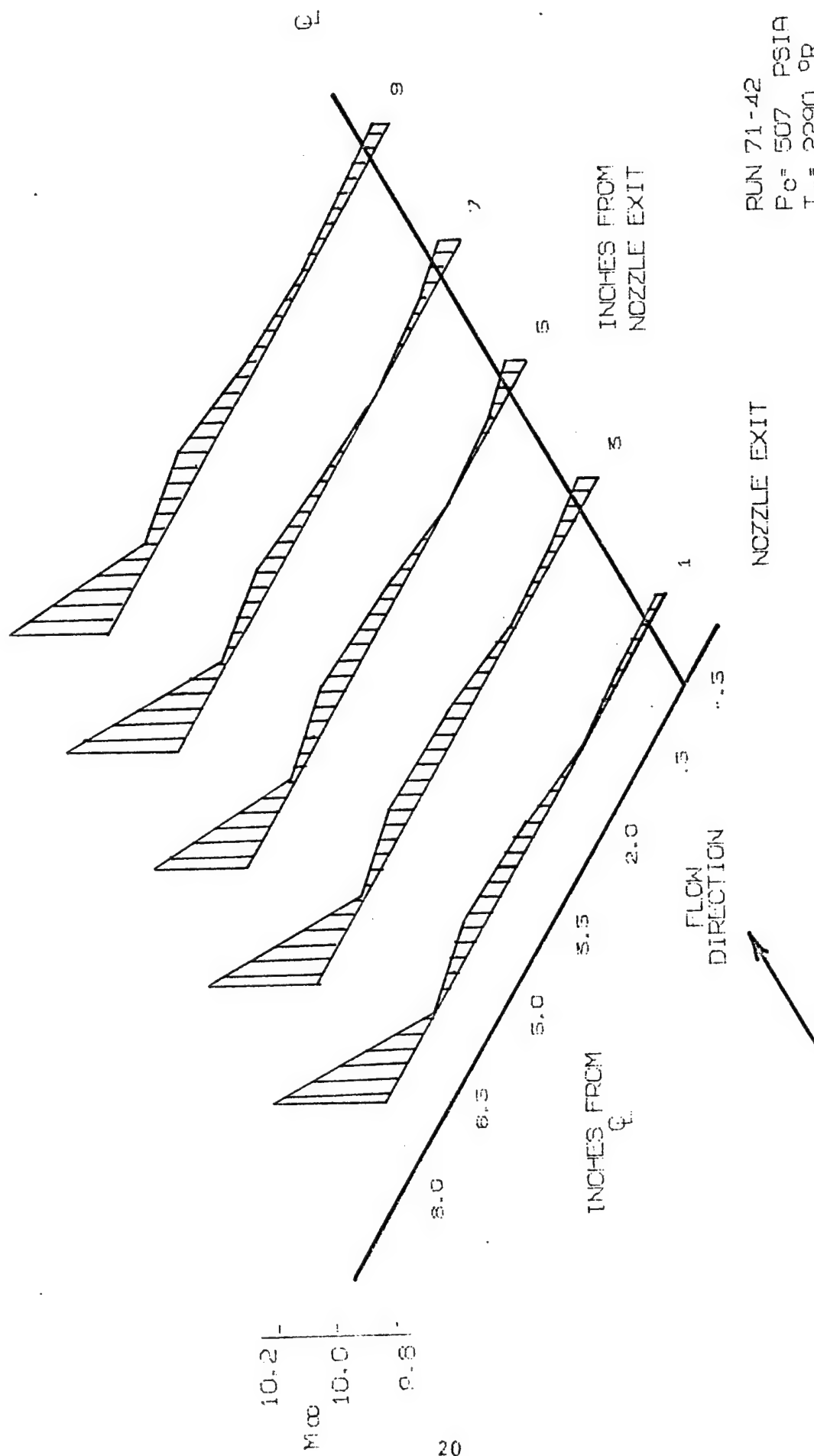


Figure 8 Mach Number Distribution $P_c = 500$ PSIA

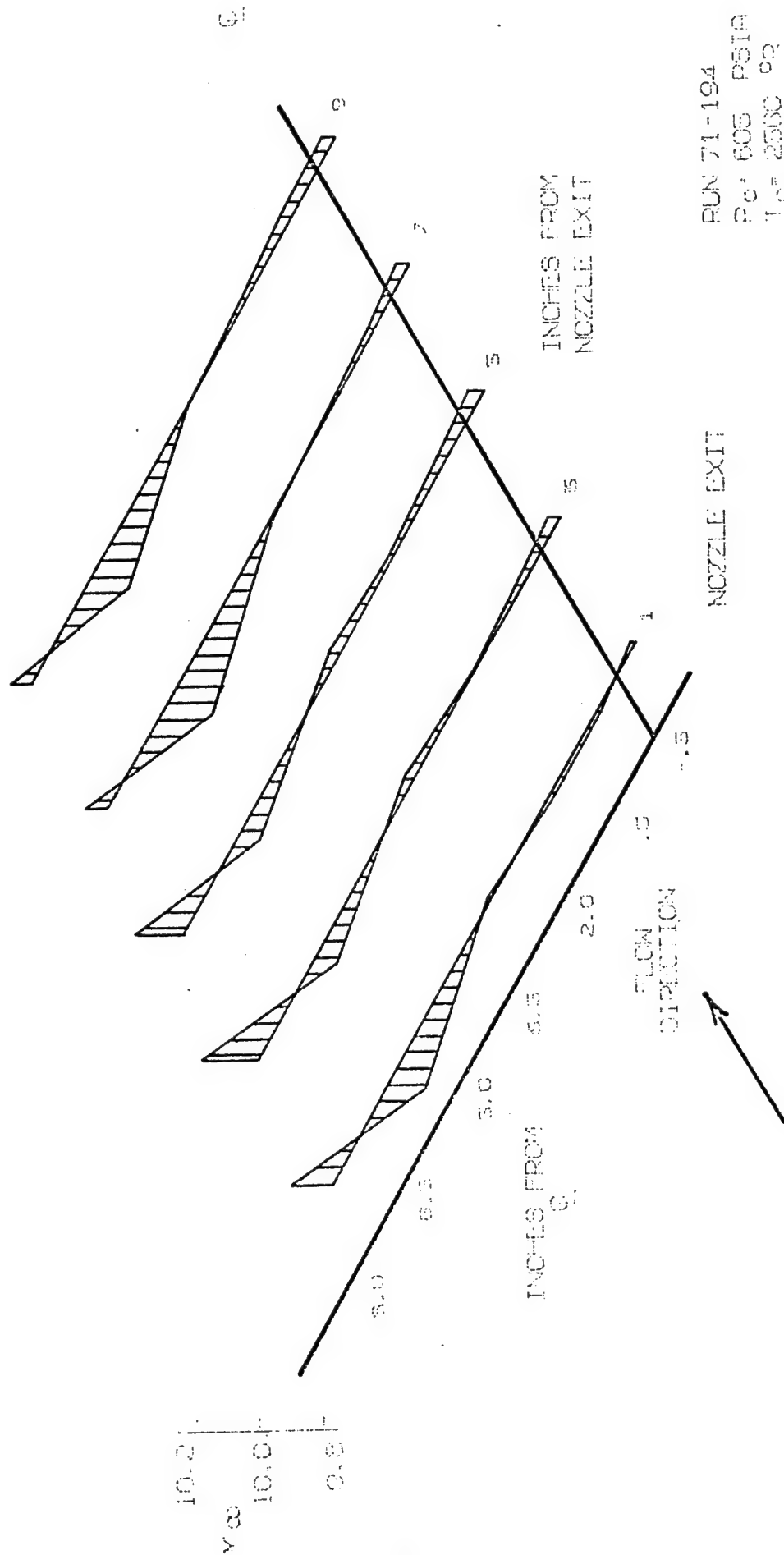


Figure 9 Mach Number Distribution $P_0 = 600$ PSIA

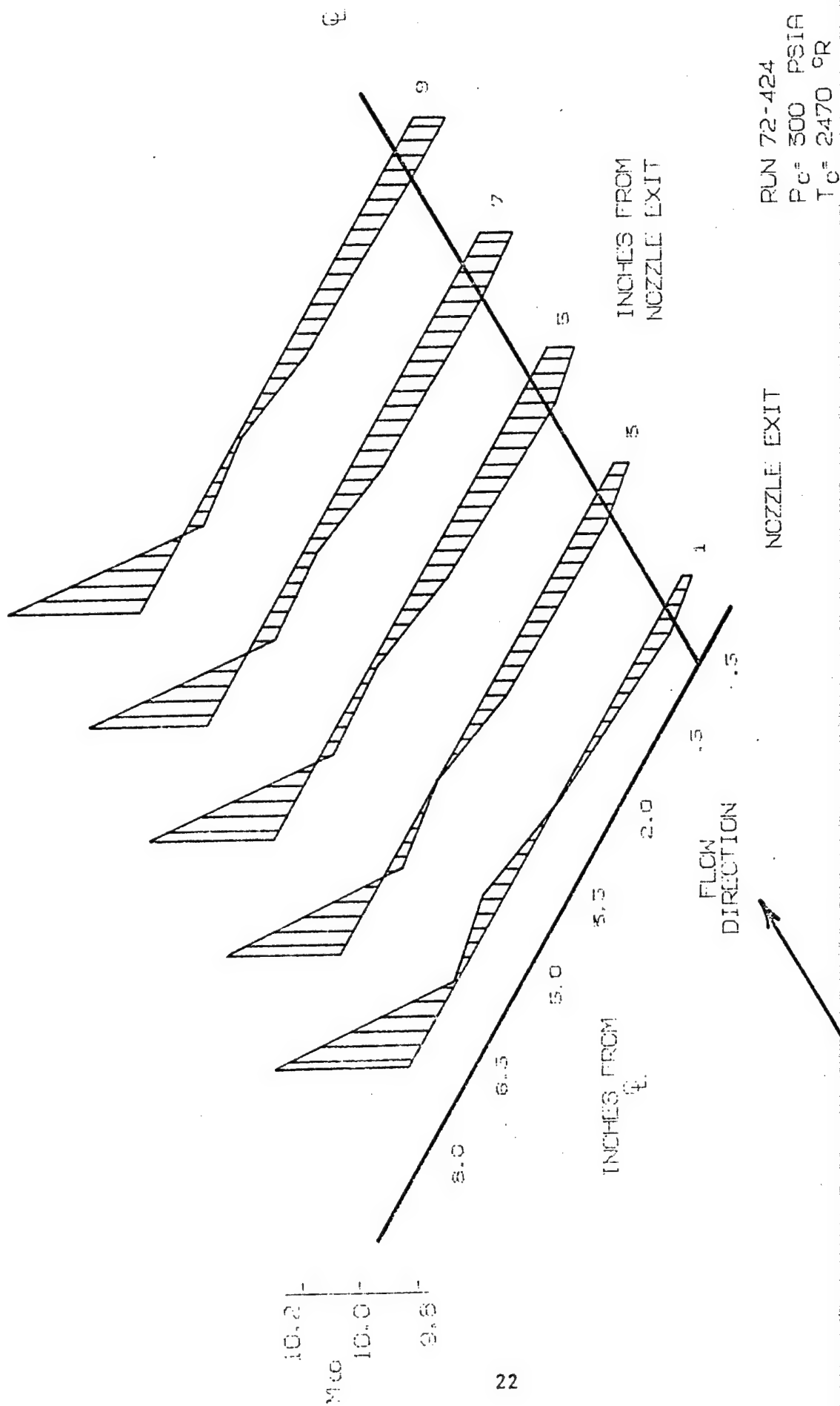


Figure 10 Mach Number Distribution $P_0 = 300$ PSIA - Water Vapor Present

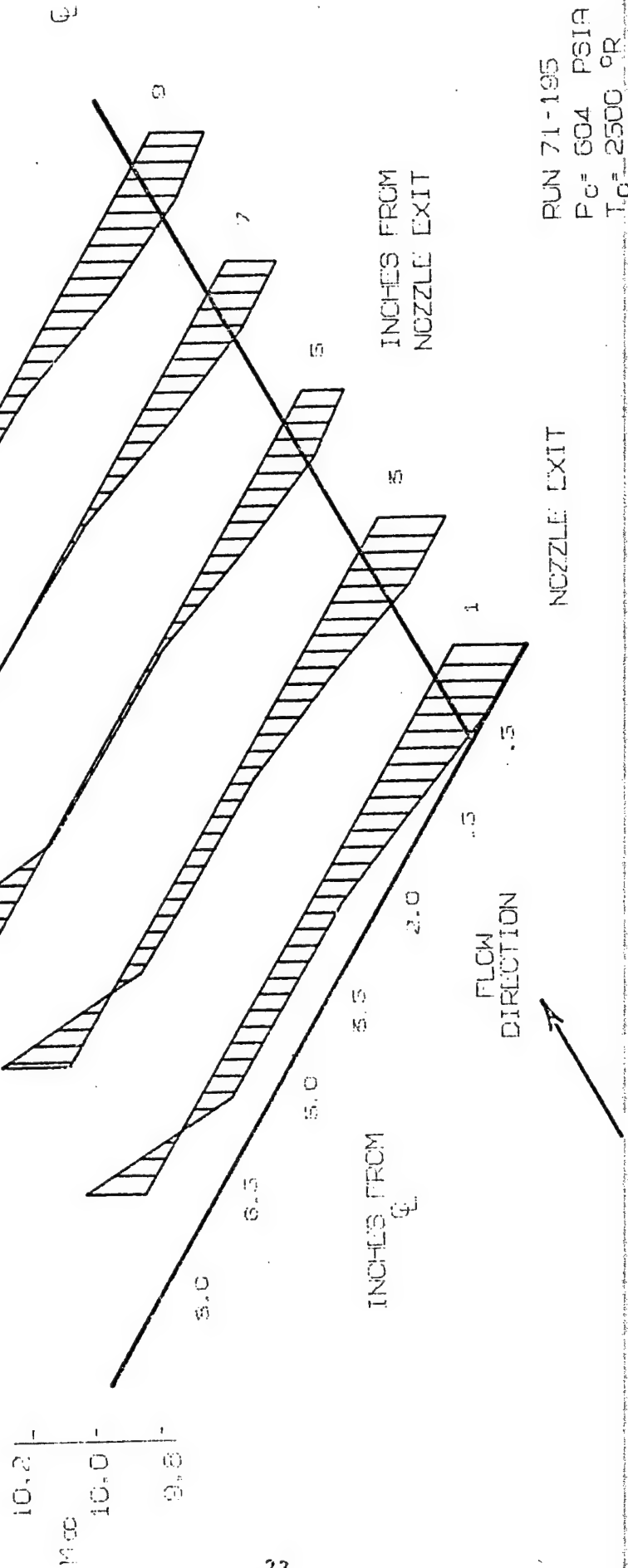


Figure 11 Mach Number Distribution $P_0 = 600$ PSIA - Water Vapor Present

Description of Facility

The AFFDL High Temperature Facility (HTF) is a hypersonic blowdown wind tunnel which uses an alumina pebble bed heater as its high temperature source. Figure 1 shows a schematic of the general arrangement of the tunnel circuit and associated systems.

The pebble bed heater is regenerated between test runs with an air-oxygen-propane burner which outputs 1.5×10^5 BTU/hr at idle conditions and 1.5×10^6 BTU/hr at maximum heating rates. The top of the alumina bed is constantly maintained at a temperature of 2000°F or higher, thus the burner operates continuously except during blow-downs. Prior to a test run, the burner is shut down and the heater evacuated to approximately 30 mm hg to reduce residual water vapor from the combustion process.

During a test run air is passed through the pebble heater at stagnation pressures from 100 to 600 psia. The heated air is then expanded through the water cooled nozzle to the open jet test section. The nozzle is a 150 inch long axisymmetric Mach 10 contour with a 24 inch exit diameter.

After passing through the test section, pressure is recovered in an axisymmetric diffuser and the air is cooled by passing through a heat exchanger before entering the vacuum system. Vacuum capability consists of a 60,000 cubic foot sphere with 3 stages of vacuum pumping which provide run times up to 3 minutes.

OPERATIONAL CHARACTERISTICS

| | |
|--------------------------------|-----------------------------------|
| MACH NUMBER | 10 |
| MAXIMUM RUN DURATION | 180 SECONDS |
| STAGNATION PRESSURE | 100 TO 600 PSIA |
| STAGNATION TEMPERATURE | 1600 TO 3000 DEG F |
| DYNAMIC PRESSURE | .18 TO .88 PSIA |
| REYNOLDS NUMBER | .100 TO .550 MILLION |
| TEST SECTION SIZE | 24 IN. DIA. BY 42 IN. FREE JET |
| ANGLE-OF-ATTACK RANGE | + OR - 30 DEG |
| ALUMINA PEBBLE BED TEMPERATURE | 3,400 DEG F MAXIMUM |
| AIR STORAGE SYSTEM | 4,728 CUBIC FEET AT 2,800 PSIG |
| VACUUM SYSTEM | 60,00 CU FT SPHERE + 4 SETS PUMPS |
| RECYCLE TIME | 20 MINUTES |

MODEL PRESSURE SYSTEM

THIS SYSTEM IS A SYSTEM FOR MEASURING 48 CHANNELS OF MODEL PRESSURES IN THE RANGE FROM 1 TO NOMINALLY 200 MM-HG. FOUR DISCRETE RANGES WITHIN THIS BAND ARE PROVIDED. THE SYSTEM IS COMPLETE FOR USE OF THE TRANSDUCERS IN THE BASIC RANGES, HOWEVER CONTROLS FOR THE VARIABLE REFERENCE SYSTEM HAVE NOT BEEN INSTALLED. CONSIDERABLE OVERLAP AND FLEXABILITY WILL BE AVAILABLE WITHOUT RECALIBRATION WHEN THE VARIABLE VACUUM REFERENCE SYSTEM IS OPERATIONAL.

| BASIC RANGE | MAX REF PRESSURE | MAX RANGE |
|----------------------|------------------|-----------|
| 5 MM-HG (.1 PSID) | 25 MM-HG | 30 MM-HG |
| 15 MM-HG (.3 PSID) | 65 MM-HG | 80 MM-HG |
| 50 MM-HG (1.0 PSID) | 180 MM-HG | 220 MM-HG |
| 100 MM-HG (2.0 PSID) | 430 MM-HG | 530 MM-HG |

HTF DENSITY ALTITUDE SIMULATION
M = 10

